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Avoidance of Crack Inducement when Laser Welding Hot-formed Car Body Components – A Variable Analysis

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Abstract

The Volvo XC60 car body contains numerous parts in Ultra High Strength Steels (UHSS) in order to guarantee the structural integrity of the car in the event of a crash situation. Most of the parts are manufactured in a hot-forming process, so called press-hardening, resulting in component tensile strength in the range of 1,500 MPa. As this type of material also presents fairly high carbon content (~ 0.22%) it brings a challenge when it comes to welding. The Volvo XC60 car body is at the same time to a large extent assembled by laser welding technology. In early development stages of the project (Y413), it was observed that laser welding of hot-formed components presented a number of challenges due to the unique conditions offered by this welding method.

The presentation will thoroughly describe the modes of procedure how to avoid crack inducement during the welding operation. A variable analysis approach was used based on the present circumstances at the production facility in the Gent plant. Crucial variables at laser welding such as gap between sheets, focal point position, welding speed and laser weld position relative to the flange edge were included in a test matrix and welding trials were carried out accordingly in the Pilot Plant in Gothenburg. The paper will discuss those welding results, the subsequent analysis and plausible theoretic explanations.

From the lessons learnt in this research, the optimum laser welding parameters were then transferred to the laser welding stations in the Gent plant. There it has been proven, that also at high volume automotive manufacturing, it is possible to provide an outstanding weld quality also at such difficult pre-conditions. The presentation ends with some facts and figures and experiences from high volume series production, which also includes aspects on quality assurance.

Keywords: Automotive industry; car body manufacture; laser welding; high strength steels; hot-forming; press-hardening; welding parameters; quality assurance

1. Introduction

When Volvo Cars introduced its new CUV (Cross Utility Vehicle) model, the XC60, in late 2008, it featured the company's most laser weld intensive car body structure so far [1, 2]. Apart from the more traditional roof laser welding, other applications such as A-pillars, B-pillars and floor sills were added to the laser scope. Especially the

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A- and B-pillar welds are crucial for the structural integrity of the car body, and are therefore classified as structural welds with more stringent requirements on defect tolerances compared to the common laser welds. This means that at least 40 mm out of every 50 mm segment of the weld shall comply with the stated minimum weld width and the requirements specified in the Technical Regulation (TR) 31830062 [3]. The first and the last 10 mm of the weld shall be in accordance to the A [Stringent] quality level. Moreover, these welds are also designated as consequence class [3] joints which mean that a potential non-compliance will lead to the following:

- Risk of not fulfilling legal or governmental requirements
- Risk of disturbed function
- Risk of shortened product life
- Risk of disturbed production process (at subsequent stages)

Therefore a specific focus was put on these laser welds during product development and process evaluation, where it was necessary to establish how normal process variations would affect the quality outcome.

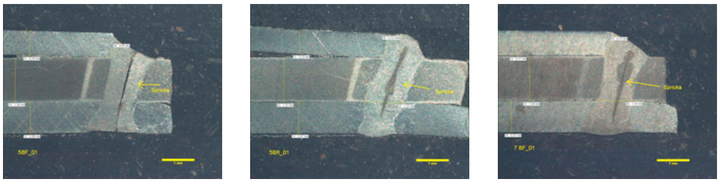
2. Background

For the B-pillar structure of the XC60 car body a Boron steel solution was chosen. The B-pillar reinforcement is a 1.5 mm thick shot-blasted Boron steel component which was spot welded to an inner part which consists of a 1.05 mm thick rephosphorized steel with a yield strength in the range of 220 MPa. Due to the severe loading conditions at a side impact the stress concentration around some of the spot welds resulted in brittle fractures in the welds and in the sheet material close to the weld circumference. This was discovered during early crash validation testing in the XC60 project. To counteract these fractures and decrease stress concentration, the spot welds in the mid-area of the B-pillar were substituted by 560 mm (front flange) and approximately 520 mm (rear flange) continuous laser welds [4]. These joints are actually three sheet metal stack-ups as the body skin panel is welded in the same operation. This means that the laser weld is a fillet weld between the exterior body side and the B-pillar reinforcement, but an overlap weld between the B-pillar reinforcement and the inner portion of the B-pillar.

During early prototype build it was experienced that cracking occurred in the B-pillar application during welding [**Fig. 1**]. Therefore, one such pillar was cut out and sent to Volvo Materials Technology for further analysis. No exceptional impurity from alloy elements such as Sulphur or Phosphorus was detected, nor a high Carbon content, and the weld geometry did not differ from the normal appearance of a laser weld. Therefore, classic hot-cracking could be excluded as the root cause of the phenomena, although the oxidized surfaces of the crack indicated that the fracture had taken place at high temperature when the weld still had a low strength.

Fig. 1. The appearance of laser weld cracking in the XC60 B-pillar during early prototype build in the Pilot Plant facilities

However, another thing observed was that the distance between the cracked weld and the edge of the flange was substantially smaller than on the opposite flange of the B-pillar. This in turn explained the low hardness since the entire flange had been annealed due to a slower cooling rate which in turn was caused by the lower mass of that flange. Previous welded car bodies had not exhibit similar visible cracks, but the new observation necessitated an analysis or earlier laser welded B-pillars. Cross section cuts were therefore performed on selected coordinates, and some of the micrographs then showed tendencies of internal cracks [**Fig. 2**].



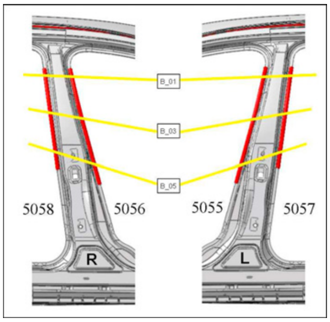


Fig. 2. Internal weld cracks revealed through micro cross sectioning.
Vertical position of the section cuts shown to the right.

Heating and cooling conditions during welding seemed to be influential factors on crack inducement, and to have a better understanding of this and to come up with proposed counteractions it was decided to run a DOE (Design of Experiments) involving some important parameters.

3. Approach of Analysis

As numerous welding trials had already been performed on coupon and component level [5], a first approach was to try to provoke the upcoming of laser weld cracks by adjusting well-known parameters such as laser power, welding speed, focal point position etc. This lead to the occurrence of stochastic cracking, which did not result in an unambiguous explanation to the cracking phenomena. Therefore it was decided to run a more scientific approach in the form of a DOE.

As variables were selected:

- The gap between the two structural parts; B-pillar reinforcement and B-pillar inner (Gap)
- The distance between the body side cut edge (= weld position) and the flange edge of the B-pillar reinforcement (Edge Distance)
- The focal point position relative to the outer surface of the body side (Focus Position)
- The welding speed

Constant parameters were:

- Laser power (4 kW)
- Inclination of welding tool (20 degrees); dependent upon accessibility in 3D complete body welding
- Pressure force (55 kg) of the clamping wheel
- Focal spot diameter (0.6 mm) at z = 0 (= focal spot on top sheet surface)
- Focal point position lateral (-0.2 mm) to the cut edge of the body side flange
- Shielding gas (Air; 30 l/min)
- Welding sequence: Rear B-pillar flange downwards, then the front flange upwards

For the variables, three levels of each parameter was to be considered, which resulted in at test matrix comprising 24 separate trials on 12 B-pillars [see **Table 1**].

Each parameter setting will give two results, one for the front flange and one for the rear flange. Response factor is no crack / crack. For the later the total crack length is measured and divided by the overall weld length which is 560 mm for the front flange and 522 mm for the rear flange. A 140 mm long crack in the front flange is specified as 140/560 = 0.25.

Penetration depth is judged according to a 10 point scale where 1 is no penetration, 10 full penetration as specified on drawing and 11 excess penetration [≥ 0.2 mm + $0.3 \times t_{\text{bottom sheet}}$; according to TR 31830062].

Table 1. Test matrix for the DOE

Run Order	Gap [mm]	Edge Distance [mm]	Focus Position [mm]	Welding Speed [m/min]
1	2	2.75	0.75	3.5
2	2	2.75	0.75	3.5
3	1	1.5	1.5	3.8
4	1	4.0	0	3.8
5	1	1.5	0	3.2
6	2	2.75	0.75	3.5
7	3	1.5	1.5	3.2
8	3	4.0	0	3.2
9	2	2.75	0.75	3.5
10	1	4.0	1.5	3.2
11	3	4.0	1.5	3.8
12	3	1.5	0	3.8

4. Results

The outcome of the DOE welding trials can be seen in **Figure 3**.

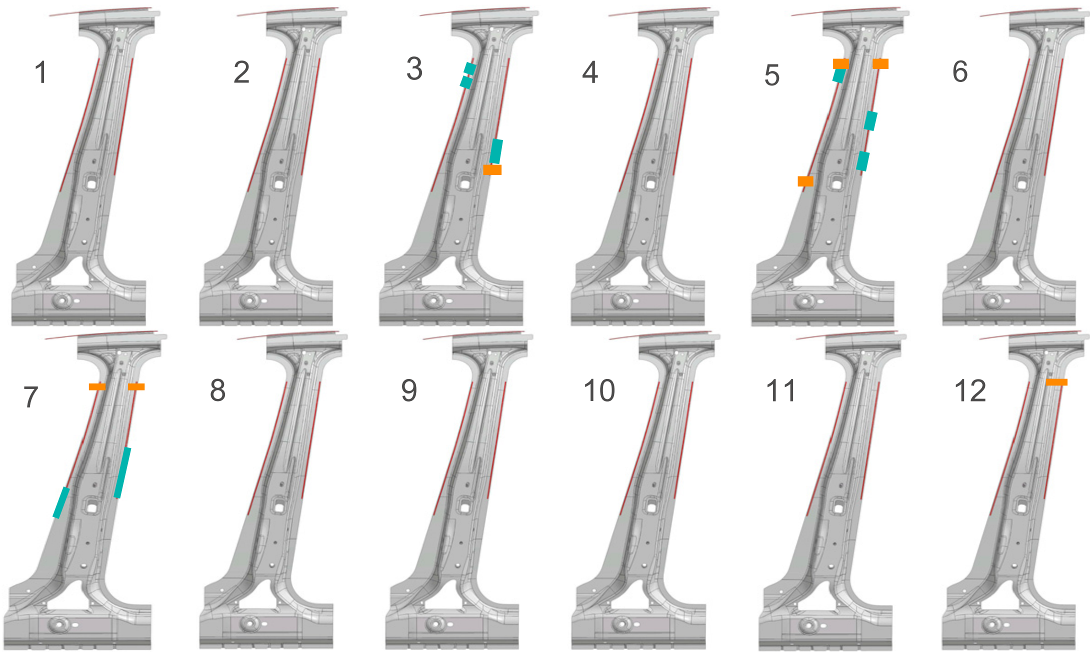
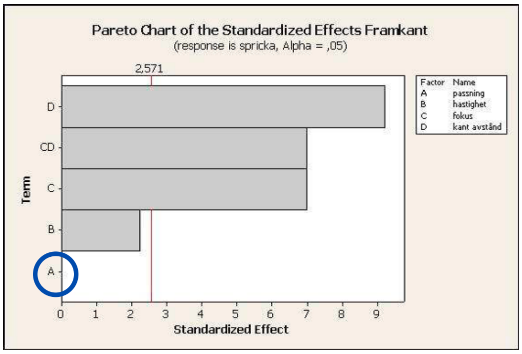


Fig. 3. Summary of DOE laser welding trials with run orders 3, 5, 7 and 12 exhibiting internal cracks (orange) and run orders 3, 5 and 7 visible cracks (green).

It was concluded that the gap between the B-pillar reinforcement and the B-pillar inner (variable A) had a neglectible influence on the crack formation [**Fig. 4**], nor could any correlation between gap and weld penetration depth be seen. The box plot illustrated in **Figure 5** shows the combined influence on crack formation between the three remaining parameters.



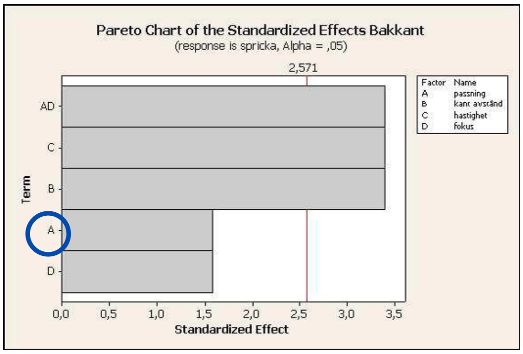


Fig. 4 Pareto charts of the effect on crack formation in the front and rear B-pillar flanges respectively, indicating that edge distance and heat input being the most influential parameters

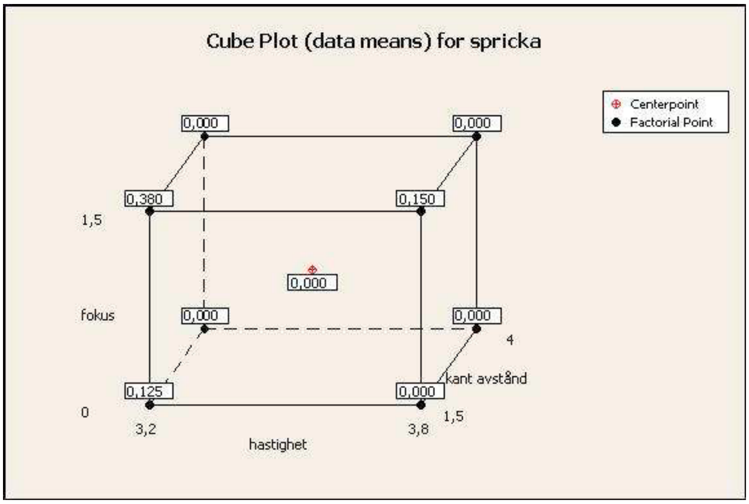


Fig. 5. Cube plot data for the probability of weld cracks with three influential parameters; edge distance, focus position and welding speed

A similar plot was created for the penetration ability, which is only influenced by the line energy, i.e. welding speed and focal spot size [**Fig. 6**], the second one in turn related to the focal point position relative to the top sheet surface. This revealed an interesting aspect regarding the later. As can be seen in the figure, the most defocused spot (z = 1.5) gave the best penetration. However this can be explained by the welding tool being tilted about 20 degrees, so that if the focal spot is calibrated in the perpendicular position to hit the top surface, this means that after tilting the focal spot ends up approximately 1.5 mm into the material resulting in a fairly defocused spot on the top surface.

Correspondingly, if the focus spot is calibrated in a position 1.5 mm above the top surface before tilting, the result will be that the highest energy density hits the top surface after tilting [**Fig. 7**]!

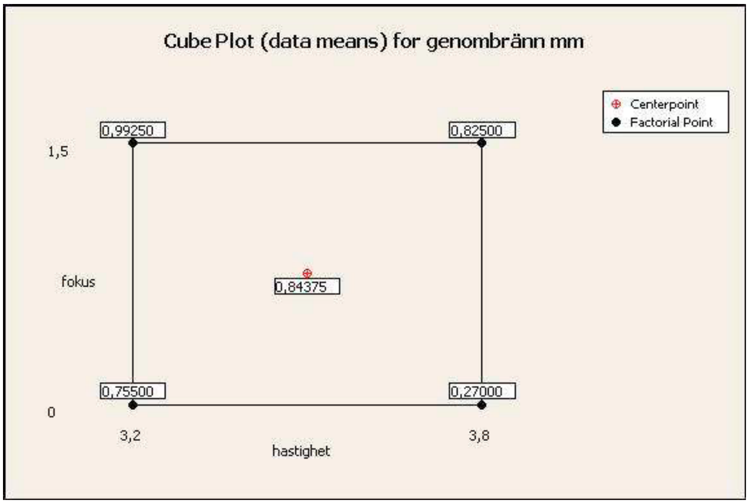


Fig. 6. Box plot data for the ability of weld penetration with the two influential parameters; focus position and welding speed

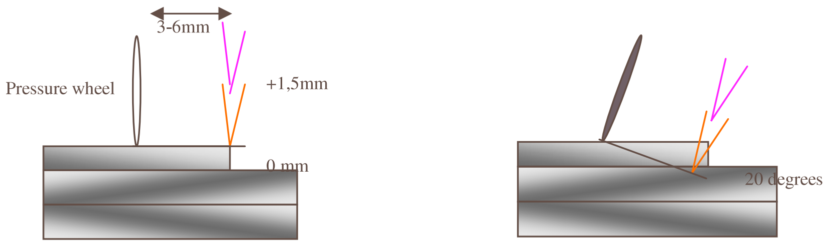


Fig. 7. The relation between calibrated and true focal point position due to the inclination of the welding tool

Calibrated FPP* [mm]	True FPP* [mm]
+ 0	- 1.38
+ 0.75	- 0.63
+ 1.5	+ 0.12

'FPP = Focal Point Position

5. Discussion

It is obvious that the heat distribution at laser welding is the root cause for crack initiation. If we take a closer look at the parameters involved they can be described according to **Figure 8**. During welding the small sheet strip between the weld location and the flange cut edge will expand due to the temperature difference, but is constricted to do so due to the surrounding material. The strip will then plasticize under the pressure, and will therefore be too short after cooling which leads to the "bow-like" separation which can be seen in **Figure 9**.

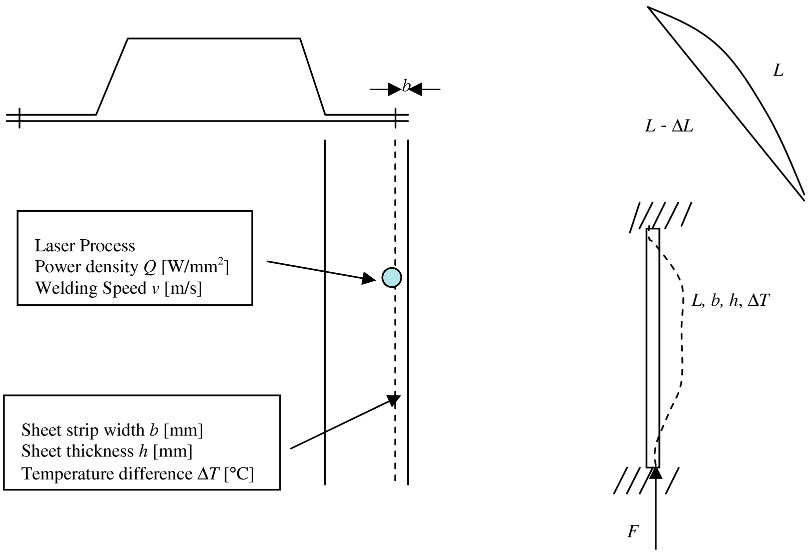


Fig. 8. The different parameters which influence the buckling behaviour of the small sheet strip, where the most influential ones are strip width (b) and sheet thickness (h)

Fig. 9. The visual appearance of the "bow-like" separation in the B-pillar region during early prototyping trials

The buckling load can be expressed as:

$$Fc \sim EI / L^2 \sim hb^3 / L^2 \quad (1)$$

The force induced due to the temperature difference (ΔT) is:

$$F \sim \Delta T \quad (2)$$

The temperature increase (ΔT) is related to the power density (Q), the welding speed (v) and the volume (b·h·L):

$$\Delta T \approx \frac{Q}{b \cdot h \cdot L \cdot v} \qquad (3)$$

Equation. (1) – (3) gives:

$$\frac{F}{F_c} \approx \frac{Q \cdot L}{h^2 \cdot b^4 \cdot v} \qquad (4)$$

From this it can be concluded that the most influential parameter is the width of the sheet strip (b), followed by the sheet thickness (h), power density (Q) and welding speed (v).

Proposed countermeasures are:

- Secure the sheet strip, *b*, to be larger than approximately 3 mm.
- Weld intermittent instead of continuous in order to minimize heat input and the risk of buckling behaviour
- Secure the correct energy density (laser power and focal point position) in order to minimize variations in heat input

6. Conclusions and Recommendations

From the discussion above it is obvious that the width between the laser weld position and the cut edge flange of the B-pillar reinforcement is the most influential factor when it comes to the occurrence of crack avoidance. Reducing the heat input by increasing the welding speed and/or defocus the focal spot could be other counter actions. However, as those countermeasures will reduce penetration depth, and there is no reliable quality assurance method than to visually observe that full penetration is achieved, adjusting those parameters was no alternative.

Therefore the focus was put on securing that sufficient distance between laser weld and flange edge is obtained. The results from the DOE indicates that with a distance shorter than 1.7 mm cracks always occur, and up to 3 mm cracks randomly appear [**Fig. 10**]. Therefore the recommendation is to have a minimum distance of 3 mm between weld and flange edge. Taken into consideration possible variations like parts deviations, cutting and assembly tolerances built on actual measurements carried out in running production of the XC60 model in the Gent plant, a recommendation for the minimum ***nominal*** distance sums up to 5 mm! [**Fig. 11**].

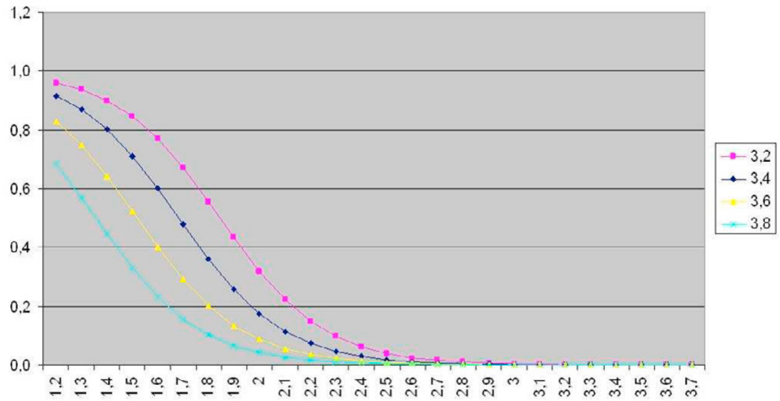


Fig. 10. Probability of weld crack occurrence in regard to different flange edge distances for various welding speeds

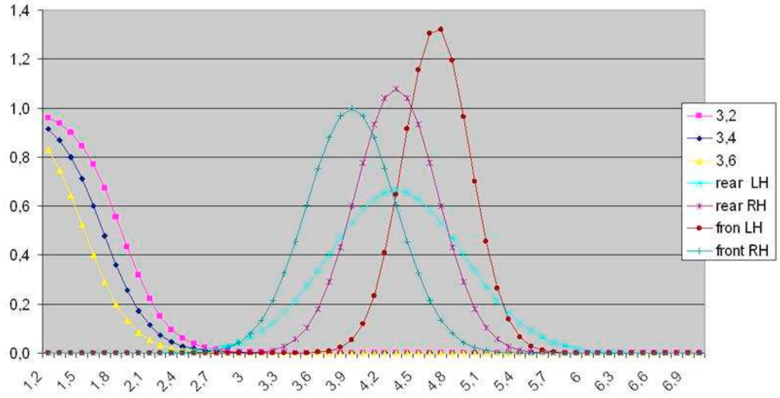


Fig. 11. Probability of weld crack occurrence for different welding speeds taking parts and assembly tolerances from production in the Gent plant in consideration

Due to the crucial importance of the positioning of the outer body side in relation to the B-pillar reinforcement a "deep dive" analysis was performed in the Gent plant in regard to tolerances on in-coming materials, assembly sequences, accuracy of fixtures, clamping forces etc. After this analysis actions were taken to centre the B-pillar portion of the body side relative to the B-pillar reinforcement and B-pillar inner in order to achieve the best possible preconditions for the laser welding operation. This was done by moving the upper reference pin in the "spider fixture" 1.0 mm rearwards in the X-direction. Such an action improved the situation considerably and the phenomena of crack occurrence completely disappeared. However, in order to guarantee a crack-free laser weld during running production, measurement protocols on the parts' relative locations are today requested from the production cell on a weekly basis. This had lead to further improvements in accurate positioning which can be seen in **Figure 12**.

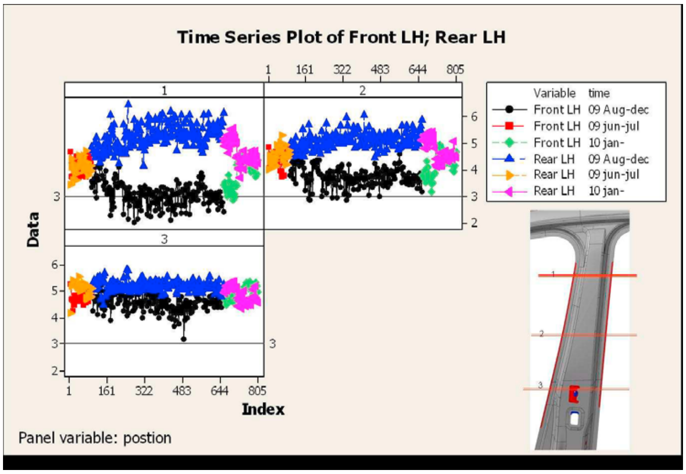


Fig. 12. Measurement protocol of the relative flange edge position on three vertical levels in the B-pillar region showing the improvement over time; from June2009 (left) to January 2010 (right)

In order to validate the quality of the structural welds of the A- and B-pillars, a set of different tools are used in the Gent body shop:

- Non-destructive testing such as on-line monitoring of 100% of the welds and 100% ultrasonic inspection utilizing a purpose developed tool
- Destructive testing such as cross section analysis at tear down following specific instructions at certain frequencies
- Regular monitoring of cover slide contamination
- Preventive maintenance according to dedicated schedules and instructions
- Spot checking of welds according to current inspection instructions

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